INTERMEDIATE PECULIAR STARS : THE Bp-Ap Si STARS.

C. Mégessier
Observatoire de Paris-Meudon
92195 Meudon Principal Cedex
France

ABSTRACT. This paper contains two parts :

1) A review of the most recent results on the silicon peculiar stars. Five topics will be reviewed : parameters of Bp-Ap Si stars - UV spectrum - spectrophotometry - spectrum variations and flux redistribution -magnetic braking.

2) The horizontal diffusion of the silicon in the presence of a magnetic field and, as a consequence, the evolution of the silicon abundance repartition in the stellar atmosphere. A first observational test is presented that supports the predicted scenario.

1. INTRODUCTION

The Bp-Ap Si stars span a wide effective temperature range between 10 000 °K and 16 000 °K. A magnetic field has been detected for each star of this group that was measured for this purpose. Among the new observational data that are continuously obtained, the spectrophotometry from the violet until the near IR and the high resolution UV spectra gives important and new information on the stellar atmospheres. Also the variations of the observed quantities as a function of the rotational period play an important part in the the progress of our understanding of the physical properties of the atmospheres.

Recently, controversial statements and observational tests have been published to precise the role of the magnetic field in the braking of the rotational velocities of the Bp-Ap stars.

Concerning the diffusion in the presence of a magnetic field, it has been predicted theoretically that during the main sequence stage of the star, the magnetic field lines guide the chemical elements in the stellar atmospheres into places where they cumulate. The case of silicon has been studied in details. The first results of an observational test are presented here.

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2. REVIEW OF THE MOST RECENT RESULTS

2.1. Some statistical properties

2.1.1. Oscillator strengths.

A paper to appear soon will be quite useful to anyone interested in the study of the silicon in the stellar atmospheres : it is a compilation of the Si oscillator strengths for all the lines between 800 Å and 9500 Å by T. Lanz and M.C. Artru (1985).

2.1.2. Effective temperatures : determination and critical discussion of several photometric estimators.

T. Lanz (1985) determined the effective temperature of 13 normal B2 to A7V stars and for 11 Ap stars with the Blackwell-Shallis method (i.e. using the integrated flux through almost all the wavelengths). He showed that the $(B2-G)_0$ Geneva photometric index is a good photometric estimator for the Ap stars for which no UV flux measurement exists, although the derived T_{eff} are higher than those obtained by means of the integrated flux. The differences may be as large as 2000 °K. The $(R-I)_c$ index may also be good but few data are available. The others photometric estimators give overestimation of the T_{eff} up to 3000 °K. Using his $(B2-G)_0$ versus T_{eff} calibration, T. Lanz gives the T_{eff} of 28 Ap stars, among them 11 are Ap Si.

These results and the discussion are important since the choice of the effective temperature is quite critical for several purposes, among them the interpretation of the stellar spectra by means of atmospheric models.

2.1.3. Spectral line intensities and statistical derived properties.

P. Didelon (1985) made visible spectra line identification and intensity measurements for a sample of 20 Bp-Ap Si stars. He looked for correlations between the metallic line strengths and other properties of the stars such as $v_e \sin i$ or magnetic field strength. Among his conclusions we may notice the anticorrelation between λ 4233 Fe II line intensity and the projected rotational velocity. One can infer that a large rotational velocity induces hydrodynamical conditions that prevent overabundances, such as built by diffusion processes. Also "the intensity of the Si I lines seems to be correlated to the magnetic field strength, which can be explained by the radiative diffusion of Si in the presence of magnetic field".

2.2. UV Spectrum.

M.C. Artru and T. Lanz are studying the UV fluxes around the well-known absorption feature at λ 1400 Å. They compare the fluxes of some Ap Si stars of which T_{eff} are around 11 000 °K and 13 000 °K to the fluxes of normal stars. Their aim is to identify unknown absorption features and to look for their effective temperature dependence (see their communication).

M.C. Artru and R. Freire are identifying high resolution IUE spectra of 10 Ap Si stars and one normal star. They first focused their attention on the Ga II resonance line at λ 1414 Å (see their communication).

Takada-Hidai et al (this Colloquium) also identified GaII in UV spectra of CP stars.

2.3. Spectrophotometry.

In their extensive series of spectrophotometric observations, Pyper and Adelman (1985) measured recently the two Ap Si stars Cu Vir and HD 34452. The fluxes are well represented from 3300 Å up to 6000 Å by a single atmospheric model, which is not frequently the case among Ap stars which Balmer jump is generally smaller than those of normal stars. Cu Vir, which presents small λ 4200 and λ 5200 absorption features, is silicon variable, whereas HD 34452 which presents a strong λ 5200 absorption feature is not. However, Shylaja and Babu (1985) who observed also HD 34452 photoelectrically found variations centred around λλ 4200, 5200, 5700, and 6300 Å, as well as apparent variations of the continuum. So, for that star, the question is opened : are there variations or is the precision of the measurements questionable ? In any case the comparison between both stars is interesting.

2.4. Spectrum and flux variations.

Hempelman et al (1984) used TD1 spectrum of HD 170000 to test the influence on the UV spectrum of the presence of two spots on the stellar surface. They pointed out the effect of Fe II and Si II line intensities within the spots.

Iliev (1984) used visible and UV spectra to study the variability of HD 27309. Si, Fe, and Ti line intensities vary by about 40 % over the cycle of the star. He measured the blocking and showed that the spectrum variability causes the observed photometric variations. The continuum flux variation is crucial. The redistribution of the UV flux to the visible region is confirmed for that star.

2.5. Magnetic braking.

The large magnetic field of Bp-Ap stars is commonly involved to explain their low rotational velocities as compared to those of normal stars. The question arises to know whether the magnetic braking occurs before or during the main sequence stage of the star. Hartoog (1977), who made a statistic (over a sample of 25 Ap stars belonging to 9 open clusters), found no correlation between ages and projected rotational velocities. Abt (1979) distinguished the Ap Si stars from the cooler Sr Cr Eu Ap stars and he thus showed that for Ap Si stars v_e sin i decreases with the age. Wolff (1981), who increased the sample used by Abt, found a correlation between age and v_e sin i for Ap Si stars, but not between effective temperature and v_e sin i. She concludes that the magnetic braking should occur on the main sequence since the times spent before the main sequence are too much short to produce differential effect as a function of the time.

More recently, Klochkova and Kopylov (1984) and North (1984) infirmed this conclusion. The former did not get a correlation of the rotational velocities neither with the age nor with the stellar temperature. They conclude that the angular momentum of each star is obtained at its earliest stage or even during the stellar formation. North (1984) compared the period distributions as a function of the time, based on theoretical magnetic braking mechanisms, with the observed period distributions. His conclusion is that the magnetic braking mechanisms involved are too much efficient to explain the observed distributions, the hydrodynamical rotational braking proposed by Fleck (1980) being far too much efficient than the accretion theory proposed by Mestel (1975). North found that the Si stars do lose their angular momentum before the main sequence phase. The old Si stars have essentially the same periods as the young ones, though the shortest periods are absent among the oldest stars. The conservation of the angular momentum during the star evolution on the main sequence star is sufficient to account for the observed periods. North presents a new study in this colloquium which would confirm these conclusions.

In all these studies, the assumptions have to be discussed carefully. If it seems that the stars are slowed down during their main sequence stage, the question of the effectiveness of the magnetic braking, either before or during the main sequence stage, is not completely cleared up.

3. THE HORIZONTAL MIGRATION OF SILICON IN THE ATMOSPHERES OF Bp-Ap STARS. TIME DEPENDENT SILICON REPARTITION ON THE STELLAR SURFACE AND FIRST OBSERVATIONAL TEST.

We first remember the main principles of the diffusion in the presence of a magnetic field which give rise to ovserabundances tied to the magnetic field geometry. Then we give the main results obtained for the silicon. A first test of the predicted effects, based on field stars, is presented.

3.1. The theoretically expected scenario.

3.1.1. Diffusion in the presence of a magnetic field-general pattern.

The diffusion in the absence of a magnetic field gives rise to vertical displacements of the atoms in the stellar atmosphere (Michaud 1970). Using Chapman and Cowling (1970) results, Michaud, Mégessier and Charland (1981) showed that, in the magnetic stars, the ions are trapped by the magnetic field lines. Thus, everywhere these lines are inclined on the stellar surface, the ions diffusion velocity will have both a vertical and a horizontal component v_V and v_H, the latter being the smallest (see Fig. 1). The analytical expressions of v_H and v_V are given in Michaud et al (1981), Alécian and Vauclair (1981) and extensively in Mégessier (1984).

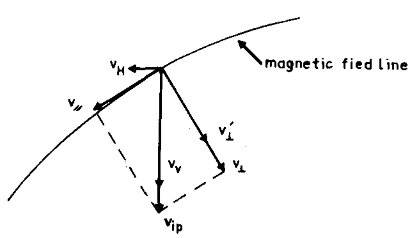

Fig. 1 : The vertical diffusion velocity v_{ip} splits into $v_{\parallel}$ which is parallel to the magnetic field line and $v_{\perp}$ which is perpendicular to it. The perpendicular component $v_{\perp}$ is reduced, due to the magnetic line ($v_{\perp}'$). Finally, one gets v_H and v_V, respectively parallel and perpendicular to the stellar surface.

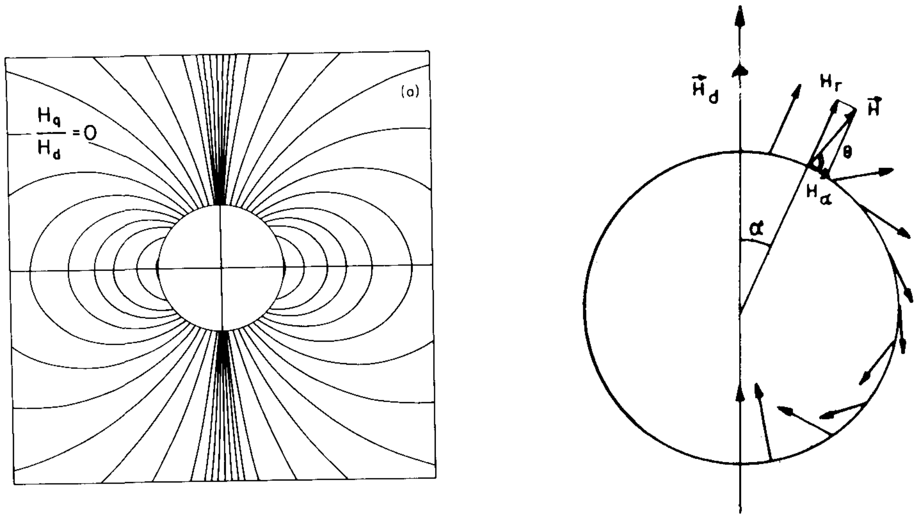

Fig. 2 : **a) The magnetic field lines in the case of a dipolar field.**
b) The corresponding local magnetic field on the stellar surface.

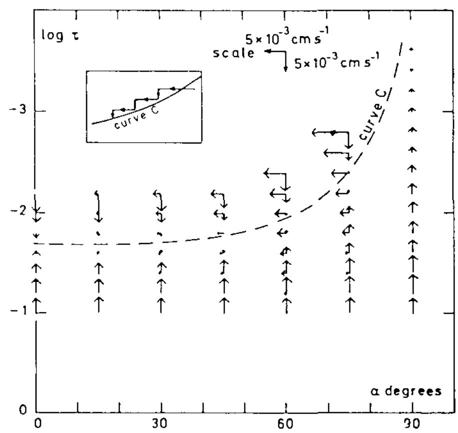

Fig. 3 : **The local vertical and horizontal components of the diffusion velocity as a function of the optical depth τ and of α, where α refers to the position on the stellar surface (see Fig. 2a). At the magnetic pole $\alpha = 0°$ and at the magnetic equator $\alpha = 90°$. The dashed line C is the locus where $v_z = 0$. The insert shows the displacement of an ion along the curve C.**

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Due to the geometry of the magnetic field, these two components are a function of the position on the stellar surface and on the optical depth. Figure 2 gives both the shape of the magnetic lines for a dipolar field and the field strength as a function of the stellar latitude.

3.1.2. The case of silicon-time dependent diffusion.

Vauclair et al (1979) and Alécian and Vauclair (1981) computed the radiative forces on the silicon atoms. Due to the horizontal magnetic field lines, the silicon as a whole is prevented to sink and overabundances by factors up to 100 can be supported in the upper atmosphere. Michaud et al (1981) showed that the horizontal velocity is enough to allow the silicon atoms to migrate from the magnetic equator up to the magnetic poles in times shorter than the stellar life time, thus giving rise to different aspects of the star depending on its age. Mégessier (1984) studied in details the case of silicon. She computed the vertical and horizontal velocities of the silicon everywhere in the stellar atmosphere above the line forming region, from the magnetic equator up to the magnetic pole (see Fig. 3). The overabundances locally supported are depending on the inclination of the field lines on the horizontal. They are the largest at the magnetic equator and they decrease regularly up to the magnetic pole.

a) *Silicon fluxes in the atmosphere and predicted scenario.*
One may schematically summarize the situation as follows (see Mégessier, 1984). The atoms reach very quickly the optical depth where their vertical velocity cancels (less than 10^5 years) ; then they move slowly from the magnetic equator towards the magnetic poles under the optical depth where $v_z = 0$ (see curve c in Fig. 3). The horizontal displacements are such that the atoms moving up in the equatorial region can arrive near the magnetic poles in times shorter than the stellar life time.

The following scenario is expected. In the stars younger than $5\ 10^7$ years, silicon is overabundant everywhere on the surface with a large maximum of abundance in a wide equatorial belt covering about one third of the stellar surface. After $5\ 10^7$ or 10^8 years there exists no more equatorial maximum and the silicon is less overabundant everywhere else on the star. For the oldest stars, older than $5\ 10^8$ or 10^9 years, small overabundance remains only in the two polar caps.

b) *Expected observational trends.*
From the scheme described above the silicon overabundance depends on three factors : the effective temperature, the magnetic field strength and the stellar age. Larger overabundances are supported higher in the upper atmosphere when the effective temperature is larger. Given the effective temperature, stronger the magnetic field, larger the silicon overabundance. The largest silicon overabundances are expected in the youngest stars.

An observational test of these effects is in progress, mainly using observations of Bp-Ap Si stars in open clusters. A first tentative test is presented here using field stars.

3.2 Observational test (Mégessier, 1985).

3.2.1 The data.

The data are collected in Table 1. We chose stars for which homogeneous values were available for the three parameters : T_{eff}, magnetic field, evolution estimator, and for the silicon abundances.

a) Effective temperatures and silicon abundances.
Homogeneous values of T_{eff} were obtained by means of the $(u-b)_0$ index calibrated as a function of T_{eff} (Matsushima 1969, Mégessier 1971). This index has been shown to be good enough for Ap stars when one needs to compare the stars in a sample (A discussion will be presented in a following paper). We used the silicon abundances determined by Mégessier (1971).

HD	$T_{eff\,(u-b)o}$	W(Hγ)	[Si/H]	$\|He_{max}\|$
173650	10 700	8.7	1.2	700
77350	10 375		0.3	470
133029	12 000	10.0	1.8	3 270
18296	11 900	8.6	1.2	1 350
219749	12 175	8.4	1.3	
112413	12 200		1.1	1 600
169952	12 600	8.3	1.8	
213871	12 600	8.3	1.5	
193722	12 600	7.5	1.3	
179527	12 600	6.8	1.2	
172761	12 800		0.0	590
27309	13 300	8.5	1.7	
224801	13 000	8.3	1.6	2 270
124224	13 700	8.1	1.3	1 260
21590	13 300	7.6	0.9	
224166	13 300	7.4	0.9	
25823	14 800		1.4	700
12767	14 800		0.75	290

Table 1

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b) The magnetic field strengths.
The magnetic field is known only for 10 stars among the 17 stars of our sample. We considered the absolute value of the field maximum measured photographically by Bascock (1958) for 8 stars and we added two values measured photoelectrically by Borra and Landstreet (1980) and Landstreet et al (1975).

c) Age estimator.
The field stars exhibit a small but detectable evolution effect. Cramer and Maeder (1980) showed that the ages of the Ap stars of the main sequence are comprised between 1.5 10^7 and 3.2 10^8 years. From Mégessier (1984), at 1.5 10^7 years the silicon maximum centered on the magnetic equator is still present. After 3 10^8 years this maximum has disappeared and the overabundance elsewhere on the stellar surface is less strong than earlier.

For stars with spectral types earlier than A0, the Balmer lines equivalent widths may be used as a criterion of luminosity. Hδ and Hγ equivalent widths were measured for most of the stars studied in Mégessier (1971). The values of Hγ, available for 12 stars of our sample are given in Table 1.

3.2.2 Comparison between the observations and the predicted schenario.

Since the scheme we predicted depends on three parameters, we have to disentangle them.

a) Effective temperature and age effects.
The plot of the silicon abundances as a function of T_{eff} gives a cloudy pattern (Fig. 4). However, considering only the stars with the same Hγ equivalent width ($8.3 \leq W(H\gamma) \leq 8.7$ Å), i.e. with the same absolute magnitude, one gets a correlation between silicon abundances and T_{eff} (Fig. 4). The abundances increase with T_{eff}. This is in agreement with our prediction. Indeed in the HR diagram, along a line of constant M_V, the ages increase while T_{eff} decreases. Well the hottest and youngest stars are expected to show larger overabundances than the oldest and coldest ones.

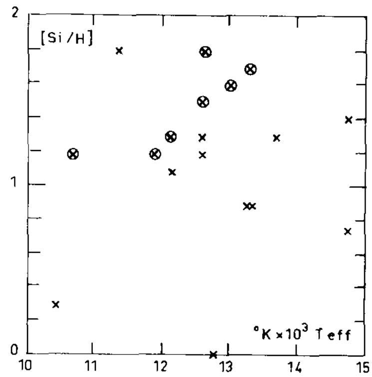
b) Evolution effect.
To detect the age effect, we have to consider stars with same T_{eff}. It is why we arranged the data in Table 1 in sets of stars with about the same T_{eff}. For a given effective temperature, the silicon abundance decreases with the age (Fig. 5) as expected theoretically.

c) Magnetic field effect.
For a given effective temperature, the silicon abundance increases with the field strength, which is predicted theoretically (Fig. 6).

3.3 Conclusion.

Until now, the studies of the diffusion in the presence of a magnetic field do not take into account several effects which could modify the simplest scheme remembered here. Effects such as microturbulence and meridional circulation were mentioned by Michaud et al (1981). However, they would not strongly modify the main trends. The first observational test presented

Fig. 4 : The silicon abundance as a function of the effective temperature. The circled crosses are the representative points for the stars with : 8.3 ⩽ W(Hγ) ⩽8.7 Å, i.e. with about the same absolute magnitude.



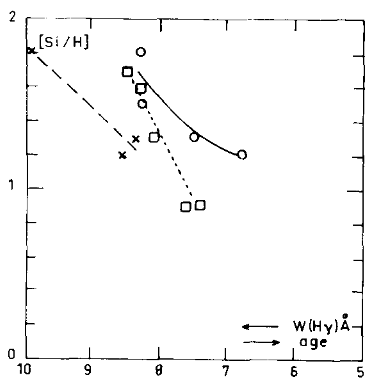
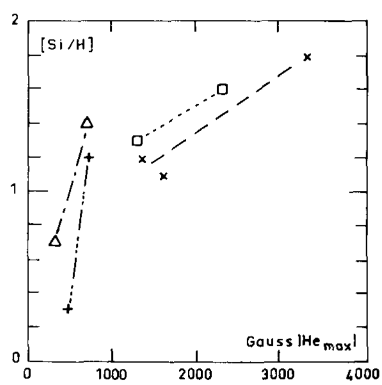


Fig. 5 : Silicon abundance as a function of the stellar age. Crosses : T_{eff} =11000, 12000°K ; circles : T_{eff} ≃ 12600°K ; squares : T_{eff} ≃13300°K. For a given effective temperature the silicon abundance decreases as a function of the stellar age.

Fig. 6 : Silicon abundance as a function of the maximum magnetic field strength. Symbols as in Fig. 5. Latin crosses : T_{eff} ≃ 10500°K ; stars : T_{eff} ≃ 14800°K. For a given effective temperature the silicon abundance increases with the magnetic field strength.



here clearly support the expected dependence of the silicon abundance on the three parameters : effective temperature, magnetic field strength and stellar age. If this first test is confirmed, it will be a strong support for the time dependent diffusion in the presence of a magnetic field, even if other phenomena have to be taken into account. Particularly, the dependence on the stellar age is a strong indication of the horizontal atoms migration along the magnetic field lines.

4. GENERAL CONCLUSION.

From the recent works, we can see that the increase of observational data confirms the general tendencies already known for Ap Si stars (and also for the other sub-types) : periodic photometric, line intensities and profiles variations, flux variations within and outside of the large spectral features (λ4200, 5200, 6300 Å). The correlation between these depressions and the other stellar properties has still to be improved ; it is not yet understood. This flux redistribution is confirmed by the study of some more individual stars. Progress are noticeable in the knowledge and the interpretation of the UV spectra although a great deal of work has still to be done in that field. Among other absorbents the role of silicon is stressed even if far to be completely explained. The role of the magnetic field to produce the surface inhomogeneities, mainly for the silicon, yields to a global description of the abundance in the atmosphere and to its stellar age dependence.

We feel that parts of the puzzle take place but the whole description of all phenomena acting in the Ap stellar atmospheres has not yet still arised and numerous fields of investigation are opened.

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